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Correlation between Hurricane Sandy Damage along the New Jersey Coast with Land Use, Dunes and Other Local Attributes

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16. Abstract

The goal of this study was to evaluate the effectiveness of sand dunes along New Jersey's Coast in reducing damage during Sandy. The study area included eight selected zones with different damage levels from Ocean County. A model to independently predict the damage level was built from the literature and field observations. We used a classification of the damage developed by an independent group, which had classified the damage at 89 blocks by the beach in Ocean County, New Jersey into severe, moderate, low and none. LIDAR data and site visits were used to measure dune attributes, such as height and width, as well as type of land use beyond the beach (boardwalk, building).

Statistical analyses, mainly ordered logistic regression and multiple linear regression, were used to estimate the relationships among damage and the predictors. The analysis shows that dunes reduced the likelihood of damage during Hurricane Sandy. Dune width, dune crest height, height of the structure, proximity to structure and type of the structure were the strongest predictors that appeared to have decreased the negative impacts of the storm. In contrast, tall structures on the land were more likely to be severely damaged. Our pilot test accurately classified 81% of the sites that had severe to low damage into the category that had been chosen by the independent group. The results suggest a follow-up that would include a more robust measure of damage and a wider range of sites for evaluation.

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Executive Summary

The goal of this study was to evaluate the effectiveness of sand dunes along New Jersey's Coast in reducing damage during Sandy. The study area included eight selected zones with different damage levels from Ocean County. A model to independently predict the damage level was built from the literature and field observations. We used a classification of the damage developed by an independent group, which had classified the damage at 89 blocks by the beach in Ocean County, New Jersey into severe, moderate, low and none. LIDAR data and site visits were used to measure dune attributes, such as height and width, as well as type of land use beyond the beach (boardwalk, building).

Statistical analyses, mainly ordered logistic regression and multiple linear regression, were used to estimate the relationships among damage and the predictors. The analysis shows that dunes reduced the likelihood of damage during Hurricane Sandy. Dune width, dune crest height, height of the structure, proximity to structure and type of the structure were the strongest predictors that appeared to have decreased the negative impacts of the storm. In contrast, tall structures on the land were more likely to be severely damaged. Our pilot test accurately classified 81% of the sites that had severe to low damage into the category that had been chosen by the independent group. The results suggest a follow-up that would include a more robust measure of damage and a wider range of sites for evaluation.

1. Introduction

It may not be easy to notice but the beaches are always changing. The movement of the ocean continually takes sand away from one beach and deposits it somewhere else. A natural dune system is a series of mounds of dry sand built by wind, waves and natural vegetation. The wind and waves move sand landward, where vegetation grows, trapping the sand. As sand accumulates, the vegetation continues to grow, and a network of roots is created to anchor the sand. As more sand is deposited on the land, the dune field begins to migrate and new dunes are formed (Eco-Tips, 2013).

Dunes are dynamic and considered as the first line of defense against surges from the sea. Dunes protect coastal towns from strong winds and waves during storms. They also provide habitat for wildlife and a recreational attraction for tourists. But how effective are they against massive storms like Sandy?

New Jersey is considered to have the most developed and densely populated shoreline in the U.S. (Stockton, 2013). The New Jersey Coastline spans around 130 miles between Sandy Hook and Cape May Point. Although there are 31.2 miles of shoreline with no human development between the salt marshes and the sea (Farrell et al., 2008), there are around 65 listed public beaches up and down the Jersey Coast. As expected sand dunes play an important role in the stabilization of the coastline of the New Jersey Shore.

Assessments of the dune systems are essential for better management and sustainability of coastal zone resources. Assessments facilitate more efficient use of limited resources (State and municipal level) by improving storm hazard mitigation activities. An assessment can be used as follows:

"

- Highlight potential problem spots in the beach-dune system
- Make more effective and efficient use of taxpayer money and municipal resources by focusing on dune maintenance and enhancement activities in areas of need
- Improve protection of beach-front homes and back-beach properties
- Evaluate the effectiveness of previous maintenance and enhancement efforts
- Aid in the enforcement of dune and shore-zone ordinances and regulations
- Aid in emergency and rapid-response planning using knowledge of where dunes are more likely to fail from stronger than normal storm activity
- Preserve a beach and dune environment that is aesthetically appealing to beach-goers

(Stockton CRC, 2013)"

Hurricane Sandy was the deadliest and most destructive tropical cyclone of the 2012 Atlantic hurricane season, as well as the second-costliest hurricane in United States history. Early on October 29, Sandy curved north-northwest and then moved ashore near Brigantine, New Jersey, just to the northeast of Atlantic City, as a post-tropical cyclone with hurricane-force winds

(Blake, 2013). Sandy caused different levels of damage along the New Jersey Coast. The effects of Sandy are less at Point Lookout, Lido Beach and Atlantic Beach, which had constructed 15-foot-high dunes as storm insurance after the Army Corps of Engineers proposed to erect dunes and elevate beaches along more than six miles of coast to protect this barrier island. On the other hand, the Long Beach City Council, which voted 5 to 0 against paying its $7 million initial share and taking part to build dunes, suffered at least $200 million in property and infrastructure losses, according to preliminary estimates (Navarro and Nuwer, 2012).

Dune barriers act like soft sea walls made of vegetation and sand that even when flattened or breached still managed to protect places like Westhampton Beach on Long Island, Plumb Beach in Brooklyn, and Bradley Beach in Monmouth County, NJ, by blunting the attack of surging waves and tides. As an example, Sand dunes at Bradley Beach were constructed in the mid-1990s at very low cost using snow fences and discarded Christmas trees to build a base of wind-driven sand that rose 15 feet, atop which dune grass was planted. These dunes limited the Sandy related damage to beach areas and homes near the shore to $3 million, while neighboring communities that had not constructed such dunes suffered much more extensive damage (Navarro and Nuwer, 2012).

Similarly, on Long Beach Island, a narrow 18-mile strip of land, some places that had a protective dune system sustained minimal damage while the other areas where there were no tall dunes suffered Sandy's destructive power (Hutchins, 2013).

An analysis of aerial imagery conducted by the Federal Emergency Management Agency (FEMA) indicated that approximately 72,000 homes and business in New Jersey were damaged or destroyed by the storm, with over 40,000 of the buildings affected located in Ocean County (Sagara, 2012).

In this study we tried to answer the following research questions: (1) How effective are sand dunes in preventing the land behind the beaches from the storm surge? (2) Which characteristics of dunes are the most effective? Are there any other factors that are effective? Thus, the goal of this study was to evaluate the effectiveness of sand dunes along NJ's Coast with a focus on Ocean County. The study area includes selected zones with different damage levels from Ocean County, and the results were grounded in the literature and field observations. This study should assist the "FEMA Flood Mitigation Research & Modeling" Project of Bloustein School of Planning and Public Policy.

Evaluating the effectiveness of sand dunes could lead to policies that would increase the service life of key facilities in transportation such as highways, rural and urban roads, bridges and railways. Strategies that reduce surge flooding increase the safety of not only people at residences but also people on roads. These strategies could also reduce the fatalities and injuries and provide a less risky transportation environment in general and a smooth evacuation during the hurricanes.

2. Literature Review

In 2002, the Coastal Research Center (CRC) at the Richard Stockton College of New Jersey commenced development of a storm vulnerability assessment for the New Jersey shoreline based on new technology called LIDAR. LIDAR is a laser light pulse sent from an aircraft to the ground and detected as a reflection from the ground and converted to an elevation based on GPS determination of the plane's position and elevation and the time for the light to reach the ground and return to the plane's detection system. Digital elevation data with points from the shoreline back landward of the dunes were collected.

An initial year 2002 project evaluated the relative effectiveness of a stretch of Long Beach Island dunes in Holgate to storm damage based on different attributes such as width, elevation, seaward slope, and vegetation density. In 2004, the Borough of Mantoloking requested that the CRC evaluate the community dune system and add the impact of multiple storms defined by the Federal Emergency Management Agency (FEMA) as an occurrence interval of every 2 years up to one every 100 years. This assessment was extended to all of the northern Ocean County shoreline by 2006, and CRC completed "Beach-Dune System Susceptibility Assessment" study for northern Ocean County in 2007, for Long Beach Island in 2009 and for the Brigantine, Atlantic County in 2010 (Stockton CRC, 2013). They have also published a 20-year report on New Jersey beach profile network regarding shoreline changes in New Jersey Raritan Bay to Delaware Bay (Farrell et al., 2008).

Copper et al. (2004) analyzed the instantaneous and historical impacts of storms on a high-energy coast in Europe. Field observations and analysis of meteorological data at the west coast of Ireland in which sand and gravel beaches are backed by large vegetated dune systems showed that factors such as wind direction, coastal orientation, interaction of wind and swell waves are critical in coastal response.

Tanaka et al. (2007) explored the structures of coastal vegetation and sand dunes, and their functions in the context of the December 2004 Indian Ocean Tsunami damage. Based on field observations and data analysis, their study covered the southern coast of Sri Lanka and Andaman coast of Thailand. Mascarenhas and Jayakumar (2008) also studied the effects of December 2004 Indian Ocean Tsunami along the coast of Tamil Nadu based on post-tsunami surveys and field observations. The study focused on the roles of dunes and forests to rescue the habitations and humankind.

Miller et al. (2001) evaluated the reestablishment of dune systems on Santa Rosa Island, Florida, which was severely impacted by Hurricane Opal in 1995. The authors analyzed different methods and experiments such as fence treatments, sand accumulation, and planting.

The devastating effects of hurricanes on low-lying sandy coasts, especially during the 2004 and 2005 seasons in the USA, have pointed to an urgent need to be able to assess the vulnerability of coastal areas and redesign coastal protection for future events, and also to evaluate the performance of existing coastal protection projects compared to ‘do-nothing' scenario. In order to address such questions the Morphos-3D project was initiated by the US Army Corps of Engineers (XBeach, 2013). This project brings together models, modelers and data on hurricane winds, storm surges, wave generation and nearshore processes. A group of experts in nearshore morphological modeling was asked to contribute by developing a new public domain model, ‘XBeach', that can predict nearshore waves and currents, dune erosion (scarping), overwashing and eventually breaching of barrier islands (Roelvink et al., 2009).

3. Methodology

After Sandy, the Geospatial Research Laboratory (GeoLab) which is the GIS and planning research unit housed in the Department of Geography and Environment at Rowan University, has flown the areas affected by Hurricane and took geo-tagged photographs of the region (Rowan GeoLab, 2013). These photographs were used to develop a damage assessment tool that scales the damage to the Jersey Shore by Hurricane Sandy in four categories as no, low, moderate and severe damage within a block.

In Phase 1 of our project, eight damaged zones (with and without dune) were selected and compared (based on the assessment of Rowan GeoLab) in order to evaluate the effectiveness of sand dunes. Then, as a second phase, five of the zones that have dune systems were studied to understand the characteristics of dunes and structures that are effective to decrease the negative impacts of storms.

After a preliminary study at Atlantic City Beach to choose key predictors, a sub-set of eight factors, shown by asterisk, were selected to be analyzed through collected data and on site observations. Statistical analyses were used to estimate the relationships among variables.

Dune Characteristics

- Aeolian dune shapes (i.e. Crescentic, Linear, Star, Dome, Parabolic, Longitudinal, Reversing)
- Dune types (i.e. Sub-aqueous, Lithified, Coastal)
- Age of dune
- Nearshore bathymetry
- Beach width*
- Dune crest height*
- Dune width*
- Foredune scarp slope*
- Gaps between dunes*
- Type of back-beach structures*
- Proximity to back-beach structures*
- Vegetation coverage
- Rehabitation

Environmental factors

- Age of the development around
- Material of the structure (i.e. wood, concrete or stone)
- Height of the structure*
- Existence of extra buffering before the structure (i.e. bush, fence, trees)
- Wind strength/direction

4. Study Area

As mentioned above, eight zones are selected which had low, moderate and severe damage based on the assessment of Rowan GeoLab. All were in Ocean County, except for one zone that is on the border of Ocean County and has no dune system (i.e. not used at the second phase of this study). Zones with different damage levels and structures (i.e. existence of a boardwalk, shops, houses, and road) were chosen to represent other local attributes. A list of zones and basic data about them are provided in Table 1.

Table 1. Selected zones

Zone Number	Has a Dune System?	County	Location	Distance
1	Y	Ocean	Seaside Heights: Between Colony Road and Dover Avenue	0.7 miles
2	Y	Ocean	Lavallette: Between Newark Avenue and Magee Avenue	0.7 miles
3	Y	Ocean	Lavallette: Between Magee Avenue and Plainfield Avenue	0.8 miles
4	Y	Ocean	Mantoloking: Between Faber Lane and Ocean Drive	0.4 miles
5	Y	Ocean	Seaside Park: Between 9th Avenue and J Street	0.9 miles
6	N	Monmouth	Belmar: Between 19th Avenue and 4th Avenue	1 mile
7	N	Ocean	Point Pleasant Beach: Between Vetrini Lane and Broadway	0.4 miles
8	N	Ocean	Seaside Heights: Between Lincoln Avenue and Hiering Avenue	0.7 miles

Zone 1 is defined by the 0.7-mile coastal area between Colony Road and Dover Avenue at Ortley Beach, Seaside Heights. This region was damaged severely during the Strom and many houses and roads are still not in use by July 2013. A section of Zone 1 is shown in Figure 1 where the upper map shows the dunes and structures at the region before Sandy (Bing Maps, 2013) and the lower map assesses the damage after Sandy (Rowan GeoLab, 2013). The assessment of Rowan GeoLab is confirmed by the severe damage shown by the red color and defined as a region where structures within the block appear to be partially or entirely destroyed. The zone is divided into 12 blocks (defined by street names) to be consistent with the measurements of GeoLab and each block was considered as a data point in the study. In this zone, the houses are usually located behind the dune or boardwalk.

Figure 1. A section from Zone 1

Zone 2 is defined by the 0.7-mile coastal area between Newark Avenue and Magee Avenue at Lavallette Beach. This region was also damaged severely during the Strom but it was almost resorted by July 2013. A section of Zone 2 is shown in Figure 2 where the severe damage shown by the red color can be seen. The zone was divided into 14 blocks to be consistent with the measurements of GeoLab and each block was considered as a data point in the study. There is a boardwalk between houses and dunes in this region.

Zone 3 is defined by the 0.8-mile coastal area between Magee Avenue and Plainfield Avenue at Lavallette Beach. The damage in this region was assessed as mostly moderate, shown by the orange color and defined as a region where debris was littered across lots, surrounding streets were filled with debris or sand as shown in Figure 3. The zone was divided into 12 blocks to be consistent with the measurements of GeoLab and each block was considered as a data point in the study. The houses are usually located right behind the dune or boardwalk in this zone.

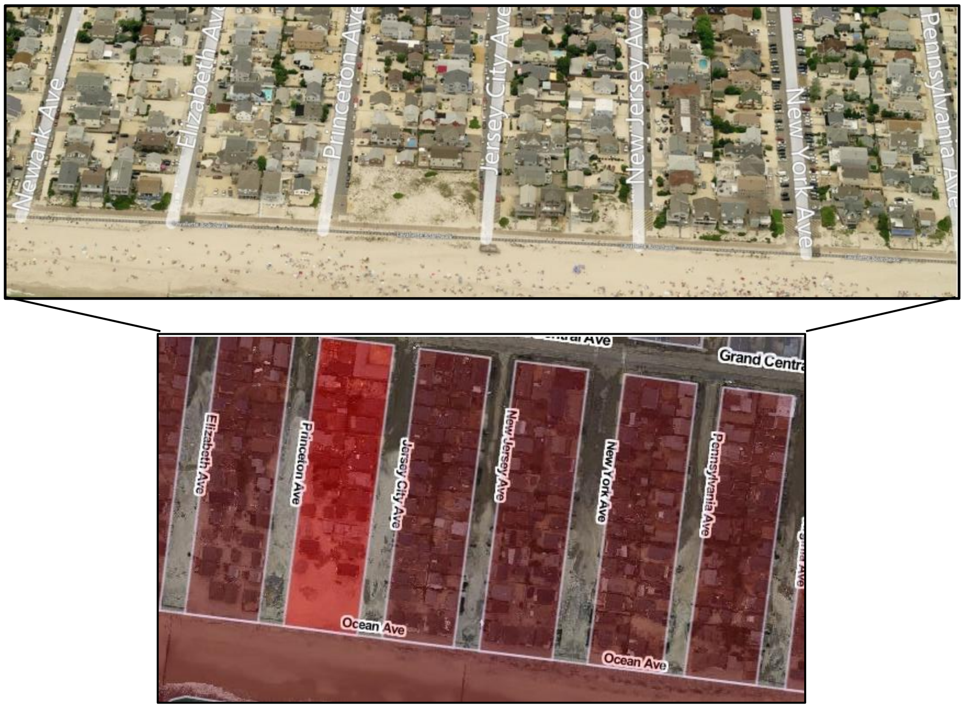

Figure 2. A section from Zone 2

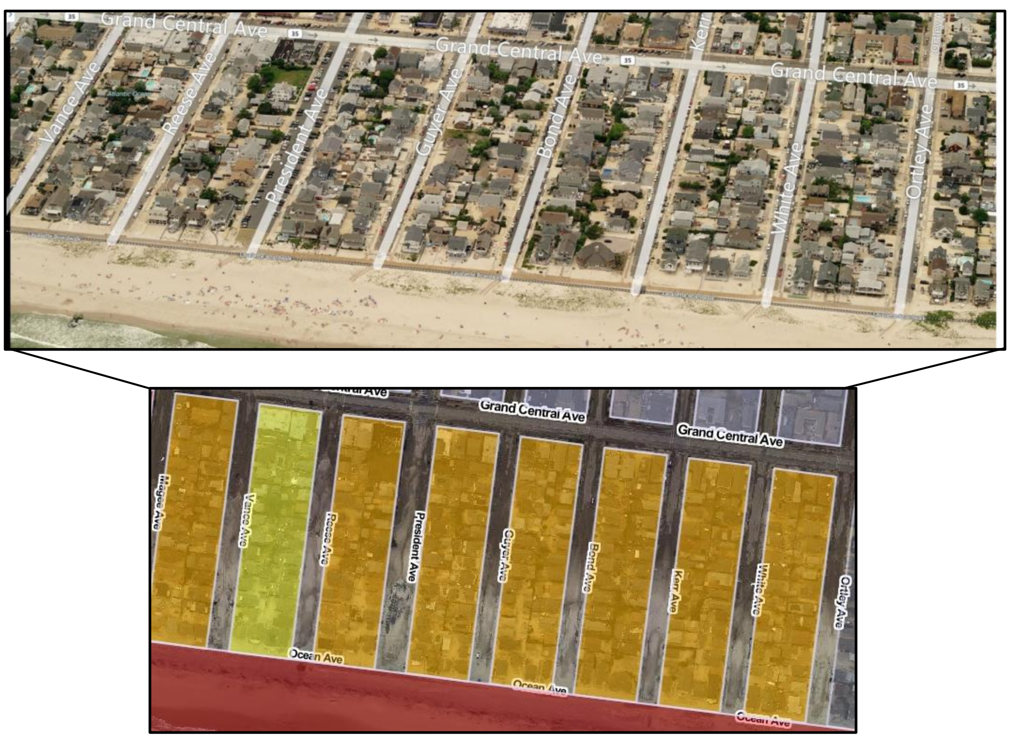

Figure 3. A section from Zone 3

Zone 4 is defined by the 0.4-mile coastal area between Faber Lane and Ocean Drive at Mantoloking. The damage in this region was assessed as moderate and low where low damage was shown by the yellow color and defined as a region where some debris may appear on the block or surrounding streets. A section of Zone 4 is shown in Figure 4. The zone was divided into four blocks to be consistent with the measurements of GeoLab and each block was considered as a data point. Observations showed that houses in this zone are located behind the dunes.

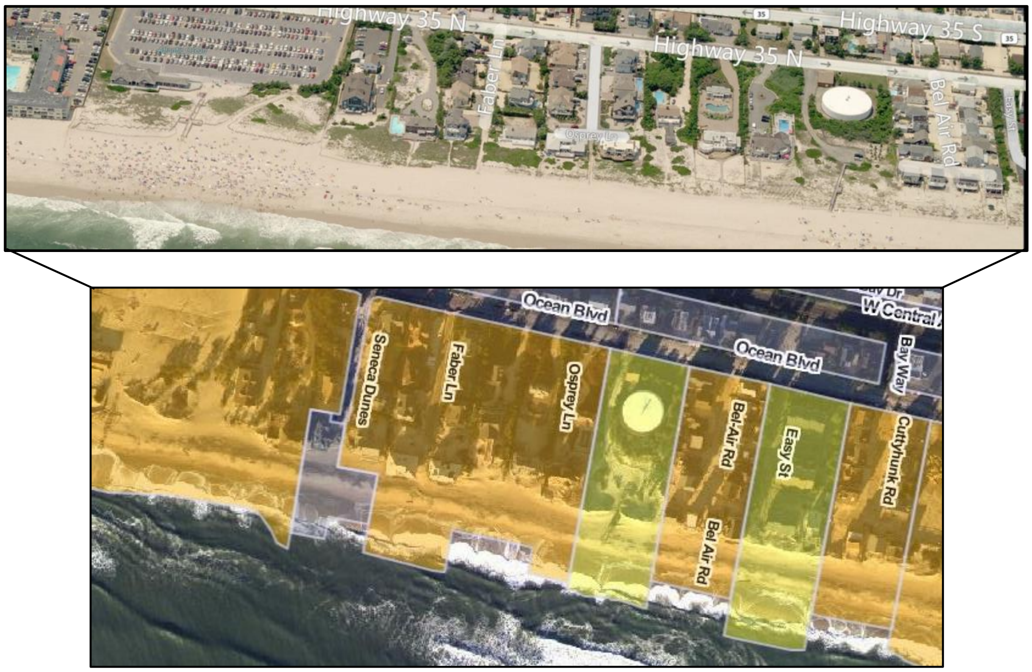

Figure 4. A section from Zone 4

Zone 5 is defined by the 0.9-mile coastal area between 9th Avenue and J Street at Seaside Park. The damage in this region was assessed as low, which is shown in Figure 6. The zone was divided into 19 blocks to be consistent with the measurements of GeoLab and each block was considered as a data point. Different than previous zones, this one has a boardwalk and a road between dunes and houses.

Figure 5. A section from Zone 5

Zone 6 is defined by the 1-mile coastal area between 19th Avenue and 4th Avenue at Belmar. Different than previous zones this one has no dune system. All levels of damage, severe, medium and low, were observed in this zone, as shown in Figure 6. The zone was divided into 13 blocks and the data show that there is a road and a boardwalk between the beach and houses. This zone is the only coastal area which is not in Ocean County but at the border of it.

Figure 6. A section from Zone 6

Zone 7 is defined by the 0.4-mile coastal area between Vetrini Lane and Broadway at Point Pleasant Beach. The damage in this region was assessed as medium and low as shown in Figure 7. The zone was divided into three blocks and each block was considered as a data point. Similar to Zone 6, this zone has no dune system but houses are located right behind a boardwalk.

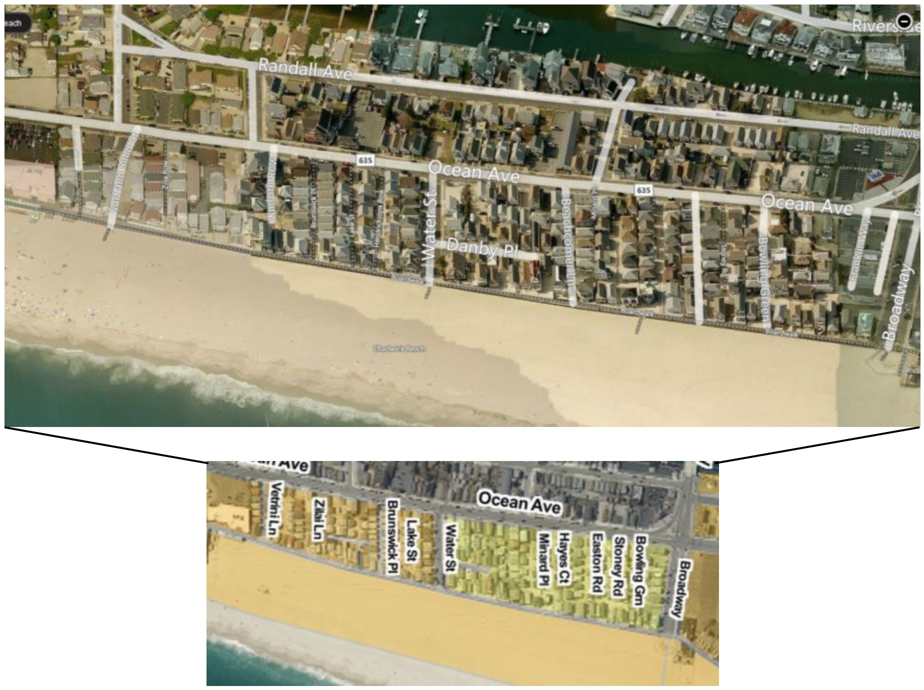

Figure 7. A section from Zone 7

Zone 8 is defined by the 0.7-mile coastal area between Lincoln Avenue and Hiering Avenue at Seaside Heights. All levels of damage (severe, medium and low) were observed in this zone as shown in Figure 8. Most of the severe damage occurred at the shore because there are no dunes in this zone and there are many stores on the boardwalk where the houses are located above a road. The zone was divided into 12 blocks to be consistent with the measurements of GeoLab and each block was considered as a data point.

Finally, Figure 9 shows an overview of the Ocean County and the start and end points of the selected zones with two closer displays.

Figure 8. A section from Zone 8

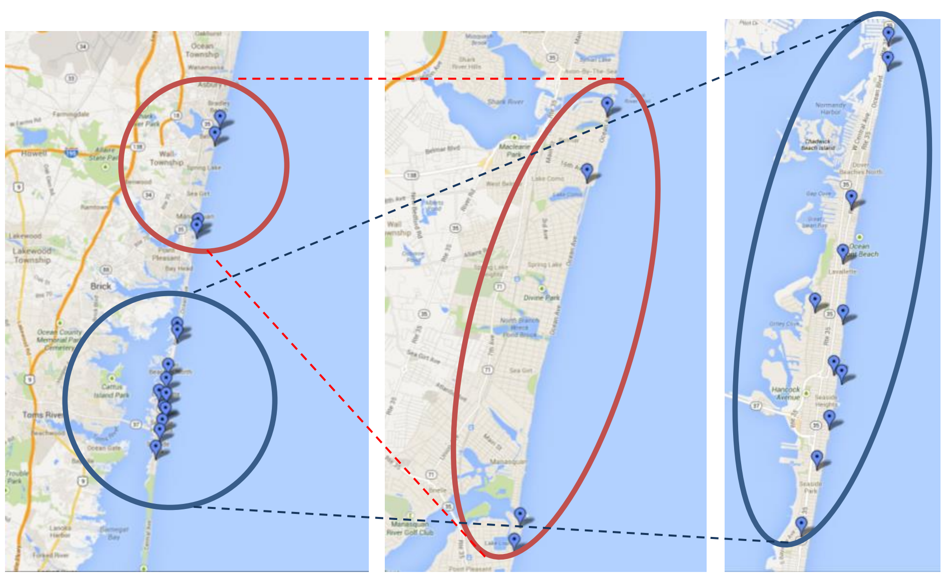

Figure 9. Overview of selected zones.
*Distance between the most northern and southern site is approximately 22 miles

5. Data Analysis

5.1. Phase 1: Evaluating the effectiveness of sand dunes

In the first phase of this study, in order to evaluate the effectiveness of sand dunes, damage levels in zones with and without dunes are compared. As mentioned above, five zones with 61 blocks (data points) have a dune system while three zones with 28 blocks have no dune system. The damage categories are scaled as 4 for severe, 3 for moderate and 2 for low damage, and the interrelation between existence of dunes and damage level is presented in Table 2 (Please see Appendix A for full data). The data shows that 57% of the blocks that are located at beaches without a dune system had severe damage during Superstorm Sandy, compared to 36% for the blocks that had a dune. In addition, Table 2 shows that blocks well protected with a dune system and had low damage (36%) compared to others which has no dune behind (14%).

Table 2. Damage level vs. Dune existence

	Dune (1) or no Dune (0)		
Damage Level	**0**	**1**	**Grand Total**
2 (low)	4 (14%)	22 (36%)	26 (29%)
3 (moderate)	8 (29%)	17 (28%)	25 (28%)
4 (severe)	16 (57%)	22 (36%)	38 (43%)
Grand Total	**28**	**61**	**89**

Although Table 2 shows the benefits of dune systems to decrease the negative impact of storms, t-test and regression analysis were performed to estimate the statistical relationship between the damage level, existence of a dune system, and other predictors.

Before performing a t-test to determine if two sets (i.e. damage level of blocks with dune and without dune) are significantly different from each other, variances of both groups are compared via F-test in order to determine the type of t-test to perform. One-tail p-value associated with the test for equality of variance is 0.208 as shown in Table 3 and it is assumed that the variances of two groups are equal and we proceeded with t-test that assumes equal variances.

Table 3. F-Test Two-Sample for Variances

	Dune (1)	*No Dune (0)*
Mean	3.000	3.429
Variance	0.733	0.550
Observations	61.000	28.000
df	60.000	27.000
F	1.333	
P(F<=f) one-tail	0.208	
F Critical one-tail	1.785	

As given in Table 4, the two sample mean values (variance) are 3 (0.733) and 3.429 (0.550). The two tailed calculated t-statistic is -2.283 and the p-value for this test is 0.025. Since the p-value is less than 0.05, this provides evidence to reject the null hypothesis of equal means. In other words having a dune or not is significantly effective on damage level.

Table 4. t-Test: Two-Sample Assuming Equal Variances

	Dune (1)	***No Dune (0)***
Mean	3.000	3.429
Variance	0.733	0.550
Observations	61.000	28.000
Pooled Variance	0.677	
Hypothesized Mean Difference	0.000	
df	87.000	
t Stat	-2.283	
P(T<=t) one-tail	0.012	
t Critical one-tail	1.663	
P(T<=t) two-tail	0.025	
t Critical two-tail	1.988	

Different than t-test, regression analysis allows you to test the direction of a hypothesized relationship (i.e. whether an increase in independent variable causes an increase or decrease in dependent variable) and the corresponding magnitude. Thus, regression analysis is performed to determine this relationship and since the dependent variable of our study is ordinal (i.e. 4 for severe, 3 for moderate and 2 for low damage) ordered logistic regression is preferred. Dune was a dichotomous 1 (yes) or 0 (no) predictor.

SAS 9.3 (SAS, 2013) output of the ordered logistic regression model is given in Appendix B. The Chi-Square Score test shows that we fail to reject the null hypothesis, that is, dunes are a significant predictor (see Table 5).

Table 5. Score test for the proportional odds assumption

Score Test for the Proportional Odds Assumption		
Chi-Square	**DF**	**Pr > ChiSq**
0.427	1	0.513

Table 6 shows the results for tests of the overall model and generalized R-square measure. They all indicate that the model is statistically significant since "Testing Global Null Hypothesis: BETA=0" indicates that the parameters are significantly different from zero.

Table 6. Tests of the overall model

Testing Global Null Hypothesis: BETA=0			
Test	**Chi-Square**	**DF**	**Pr > ChiSq**
Likelihood Ratio	4.990	1	0.026
Score	4.940	1	0.026
Wald	4.709	1	0.030

R-Square	0.054	**Max-rescaled R-Square**	0.062

The degrees of freedom, coefficients, their standard errors, the Wald chi-square test and associated p-values of the ordered regression test are given in Table 7. Existence of dune (i.e. variable called DuneNoDune) is statistically significant on the damage level of Sandy on shore. It is possible to claim that for a one unit incease in dune existence (i.e. going from 0:No dune to 1:Having dune), a 0.962 units decrease in the damage is expected in the ordered log-odds scale. This assumes that all dunes are the same and no other attributes make a difference.

Table 7. Analysis of Maximum Likelihood Estimates

Analysis of Maximum Likelihood Estimates						
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept	**4**	1	0.345	0.374	0.852	0.356
Intercept	**3**	1	1.579	0.408	14.934	0.0001
DuneNoDune	**1**	1	-0.962	0.443	4.709	0.030

5.2. Phase 2: Characteristics of dunes that are effective to decrease the negative impacts of the Storm

But dunes come in all sizes and shapes. In order to understand which characteristics of dunes and structures are effective on decreasing the negative impacts of Sandy on shore, the five selected zones with dunes were visited. Additonally data were collected using Google Earth (GoogleEarth, 2013) and year 2010 LIDAR Data from U.S. Geological Survey (USGS, 2013). LIDAR is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light, and then used to make high resolution maps. The data is processed by TerraScan and TerraModeler software (Terrasolid, 2013) in Bentley MicroStation V8i software (Microstation, 2013). The following eight parameters were collected for each block which correspons to 61 data points (Please see Appendix C for full data).

- Beach width: The average of minimum and maximum distances between each dune and sea in U.S. survey feet.
- Dune crest height: The highest point of dune relative to ground in U.S. survey feet.
- Dune width: The wideness of the dune in U.S. survey feet, measured in the middle of each block which usually represents the average width of dune.
- Foredune scarp slope: The ratio of vertical height to horizontal length where unit is %.
- Gaps between dunes: The distance between two dunes where 0 means this dune and the next dune are continuous in U.S. survey feet.
- Type of structure: The type of the first back-beach structure after dunes, 1 if it is a building, 0 if it is a boardwalk.
- Proximity to structure: The average distance between dunes and back-beach buildings in U.S. survey feet, 0 means the house is on the dune.
- Height of the structure: The average height of the back-beach structure (i.e. boardwalk or building) in U.S. survey feet.

The correlations between these variables are measured to understand the linear association between variables. As shown in Table 8, the highest correlation (0.989) is between "type of structure" and "height of the structure" which is expected since the height is less if the structure is a boardwalk, and it is higher if the structure is a building. The second highest correlation (0.790) is between "dune crest height" and "dune width", which says the wider dunes are also higher than others. The correlation analysis also shows that there is a negative correlation (-0.684) between "beach width" and "foredune scrap slope", which means that the smaller the beach the steeper the dune. However, since the beaches considered in this study are not narrower than 68 feet, this relationship is not a strong one. The last correlation coefficient higher than 0.5 (i.e. -0.534) is between "proximity to structure" and "type of structure" which means when there is a boardwalk (i.e. type 0 structure) the distance between dunes and buildings increases which makes sense.

Next, the following two types of regression analysis were performed in order to understand the characteristics of dunes or environmental conditions that were the most effective in reducing the damage level of Superstorm Sandy: ordered logistic regression and multiple linear regression.

Table 8. Correlation coefficients of the predictors

	Beach Width	Dune Width	Dune Crest Height	Height of Structure	Type of Structure	Foredune Scrap Slope	Gaps Between Dunes	Proximity to Structure
Beach Width	1.000							
Dune Width	0.388	1.000						
Dune Crest Height	0.474	0.790	1.000					
Height of Structure	-0.010	0.468	0.139	1.000				
Type of Structure	-0.043	0.433	0.104	0.989	1.000			
Foredune Scrap Slope	-0.684	-0.253	-0.179	-0.043	-0.019	1.000		
Gaps Between Dunes	-0.037	-0.164	-0.307	0.289	0.262	-0.064	1.000	
Proximity to Structure	0.229	0.052	0.022	-0.466	-0.534	-0.204	-0.076	1.000

As a starting point, the effect of each factor is checked individually. Table 9 shows the p-values and parameter estimates computed by ordered logistic and multiple linear regressions. The results of two regression techniques seem consistent with each other. The sign of the parameter estimates are always the same while their values are not comparable since the two techniques use different scales. The p-values are also not very different from each other. Additionally, it seems beach width, dune width, dune crest height and proximity to structure are the key factors.

Table 9. Dune attribuetes and Damage: Binary P-values and parameter estimates

	Ordered logistic regression		**Multiple linear regression**	
	P-value	Parameter Estimate	P-value	Parameter Estimate
Beach Width	0.0003	-0.045	0.0002	-0.016
Dune Width	< 0.001	-0.043	< 0.001	-0.015
Dune Crest Height	< 0.001	-0.638	< 0.001	-0.180
Height of Structure	0.6598	0.010	0.6213	0.005
Type of Structure	0.5190	0.370	0.4699	0.200
Foredune Scrap Slope	0.1300	0.163	0.1200	0.075
Gaps Between Dunes	0.1100	0.005	0.1700	0.019
Proximity to Structure	0.0090	-0.013	0.0100	-0.005

By using these preliminary results and observations during site visits, a few different regression models were developed by using some of these variables. The first model is composed of four variables which are easier to change with public policy compared to other variables: Dune width, dune crest height, gaps between dunes, foredune scrap slope. This model is called as "Model 1" and multiple linear regression (see Appendix D for results) and ordered logistic regression (see Appendix E for results) are used to estimate the relationship. The multiple linear regression results with a P-value that is smaller than 0.0001 for the overall model are given Table 10. The results show that among these four variables "dune crest height" is the most effective one for decreasing the severe effect of Sandy. The results of ordered logistic regression which are presented in Table 11 confirm that inference.

Table 10. Multiple linear regression results for Model 1

R-Square	0.583	Adj R-Sq	0.554

Variable	Parameter Estimate	Pr > |t|
Intercept	6.357	<.0001
DuneWidth	-0.005	0.172
DuneCrestHeight	-0.144	0.0002
ForeduneScrapSlope	0.016	0.632
GapsBetweenDunes	-0.000073	0.973

Table 11. Ordered logistic regression results for Model 1

R-Square	0.544
Max-rescaled R-Square	0.613

Analysis of Maximum Likelihood Estimates

Parameter	Estimate	Pr > ChiSq
Intercept	10.240	0.003
Intercept	12.601	0.0005
DuneWidth	-0.008	0.495
DuneCrestHeight	-0.554	0.0006
ForeduneScrapSlope	0.093	0.518
GapsBetweenDunes	0.022	0.228

The variables of the second model (Model 2) are selected from the variables that are significant in explaining the dependent variable by themselves (i.e. the variables that has P-value smaller than 0.05 in Table 9): Beach width, dune width, dune crest height and proximity to structure. The multiple linear (see Appendix F) and ordered logistic regression (see Appendix G) results are given in Table 12 and Table 13, correspondingly. The results show that when just these four factors are considered “dune crest height” and “proximity to structure” are the significant factors on reducing the negative impacts of the Storm. Also associated R-square and adjusted R-square value are higher than that of Model 1.

Table 12. Multiple linear regression results for Model 2

R-Square	0.677	**Adj R-Sq**	0.653

Variable	**Parameter Estimate**	**Pr > |t|**
Intercept	7.092	<.0001
BeachWidth	-0.002	0.549
DuneWidht	-0.004	0.145
DuneCrestHeight	-0.141	<.0001
ProximitytoStructure	-0.005	0.0004

Table 13. Ordered logistic regression results for Model 2

R-Square	0.630
Max-rescaled R-Square	0.710

Analysis of Maximum Likelihood Estimates

Parameter	**Estimate**	**Pr > ChiSq**
Intercept	15.628	<.0001
Intercept	18.509	<.0001
BeachWidth	-0.010	0.567
DuneWidth	-0.015	0.242
DuneCrestHeight	-0.574	0.001
ProximitytoStructure	-0.022	0.001

These results show that the relationship between these factors are more complex than expected and a detailed model is needed to understand which characteristics of dunes or environmental conditions are significantly effective on damage level of Superstorm Sandy. Also the assumptions of the models should be checked to end up with a coherent conclusion.

Thus, a multiple linear regression model is developed to estimate the relationship between eight explanatory variables and storm damage level (i.e. fitting a linear equation to observed data). SAS output of the multiple linear regression model is given in Appendix H.

As given in Table 14, the P-value for the regression model (<0.0001) and the adjusted R-Square of 0.682 shows that the model as a whole is a strong predictor.

The parameter estimates provided in Table 15 show that four variables were significantly effective in reducing the negative impact of Sandy. “Dune width” with a coefficient of -0.01 shows that the wider the dune the smaller the damage level. In other words, for one foot increase in dune width, 0.01 units decrease in damage is expected. Other significant factor is “dune crest height” with a coefficient of -0.115. As expected if the dune gets higher, the damage level decreases by 0.115 units for each one foot increase in dune crest height. The third effective factor is the “proximity to structure”, which is the average distance between dunes and back-beach buildings. Each one foot increase in the distance between the dunes and buildings implies a 0.004 unit decrease in damage level. When all variables are considered together, the analysis show that “height of structure” is also a significant factor. If average height of the back-beach structure (i.e. boardwalk or building) increases by one foot (the value of the house/store or boardwalk increases), the damage level is expected to increase by 0.099 units. Since the considered structures are at most 3-story houses (boardwalks are easily damaged during the Storm), they have the same resistance against very strong wind and surge (other variables being equal). Thus, a positive relationship between height and damage is not surprising.

Table 14. Multiple linear regression model results

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	31.857	3.982	17.05	<.0001
Error	52	12.143	0.234		
Corrected Total	60	44.000			

Root MSE	0.483	**R-Square**	0.724
Dependent Mean	3	**Adj R-Sq**	0.682
Coeff Var	16.108		

Table 15. Parameter estimates of multiple linear regression model

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	**1**	6.269	1.082	5.790	<.0001
BeachWidth	**1**	-0.004	0.004	-1.000	0.324
DuneWidth	**1**	-0.010	0.004	-2.470	0.017
DuneCrestHeight	**1**	-0.115	0.040	-2.900	0.006
HeightofStructure	**1**	0.099	0.050	1.960	0.055
TypeofStructure	**1**	-1.951	1.309	-1.490	0.142
ForeduneScrapSlope	**1**	-0.039	0.040	-0.970	0.336
GapsBetweenDunes	**1**	-0.003	0.002	-1.540	0.129
ProximitytoStructure	**1**	-0.004	0.002	-2.130	0.038

The sum of squared residuals (i.e. amount of error remaining between the regression function and the data set) is 12.143 which seems reasonable for 61 data points as given in Appendix H. The raw residual plot graph in the upper-left panel of Appendix H shows a pattern since there are only three discrete levels for the dependent variable. Although an ordered logistic model might be more appropriate, the plot of residual versus predicted values is quite randomly dispersed keeping in mind the structure of the dependent variable. Studentized residuals show a similar pattern, where the threshold values of ± 2 (4 out of 61) indicate outlying observations. Similarly, the residual-by-leverage plot also shows that five observations have high leverage-that is, these data points are unusual in their values relative to the other blocks. The plot of Cook's D distance versus observation number reveals these five points which are influential on the regression parameter estimates.

The normal-probability Q-Q plot in the second row and the residual histogram in the third row of the panel in Appendix H show that the normality assumption for the residuals is reasonable. The points on the plot of the dependent variable versus the predicted values do not lie along a 45-degree line and shows the same three-level pattern indicating that the model is not perfectly predicting the behavior of the dependent variable.

An ordered logit model was computed to estimate the relationship between these eight explanatory variables and storm damage level. Corresponding SAS output is given in Appendix I.

The Chi-Square Score Test for the proportional odds assumption which tests whether our one-equation model is valid or not shows that we fail to reject the null hypothesis (i.e. proportional odds assumption appears to have held) as shown in Table 16.

Table 16. Score test for the proportional odds assumption

Score Test for the Proportional Odds Assumption		
Chi-Square	**DF**	**Pr > ChiSq**
14.0232	8	0.0812

Table 17 shows the results for tests of the overall model and generalized R-square measure. They all indicate that the model is statistically significant since "Testing Global Null Hypothesis: BETA=0" indicates that the parameters are significantly different from zero.

Table 17. Tests of the overall model

Testing Global Null Hypothesis: BETA=0			
Test	**Chi-Square**	**DF**	**Pr > ChiSq**
Likelihood Ratio	72.0141	8	<.0001
Score	42.7656	8	<.0001
Wald	24.9229	8	0.0016

R-Square	0.693	**Max-rescaled R-Square**	0.781

The degrees of freedom, coefficients, their standard errors, the Wald chi-square test and associated p-values of the ordered regression test are given in Table 18. With a significance level of 5%, four parameters are significantly effective on reducing the negative impact of Sandy. Three of them are the same parameters found by multiple linear regression: dune width, dune crest height and height of structure. “Dune width” has a coefficient of -0.053 which indicates that wide dunes are more protective. A one foot increase in dune width is associated with a 0.053 units decrease in damage is expected in the ordered log-odds scale. Other significant factor, “dune crest height”, has a coefficient of -0.557. As explained above if the dune gets higher, a decrease is expected in damage level. The third common effective factor is “height of structure”. If average height of the back-beach structure increases by one foot, the damage level is expected to increase by 0.796 units (in the ordered log-odds scale). Different than multiple linear regression, ordered logistic regression results show that “type of structure” is also effective on reducing the damage level. If type of structure decreases by one unit (i.e. 1 for building, 0 for boardwalk), the damage level is expected to increases by 15.683 in the ordered log-odds scale while the other variables are held constant.

Table 18. Analysis of Maximum Likelihood Estimates

Analysis of Maximum Likelihood Estimates					
Parameter	**DF**	**Estimate**	**Standard Error**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept	1	11.741	6.342	3.428	0.064
Intercept	1	15.048	6.541	5.292	0.021
BeachWidth	1	-0.047	0.032	2.213	0.137
DuneWidth	1	-0.053	0.023	5.272	0.022
DuneCrestHeight	1	-0.557	0.247	5.105	0.024
HeightofStructure	1	0.796	0.323	6.089	0.014
TypeofStructure	1	-15.685	7.797	4.046	0.044
ForeduneScrapSlope	1	-0.103	0.233	0.194	0.659
GapsBetweenDunes	1	0.0027	0.023	0.013	0.908
ProximitytoStructure	1	-0.017	0.011	2.410	0.120

A final look at the results is provided in Table 19, which compares the actual category of dune damage versus the category predicted by our models. Fifty-one of the 61 were correctly predicted, and all of those not predicted correctly were placed in the adjacent category. While 84% were correctly predicted, the tables shows a tendency for the regression model to overpredict low damage and underpredict high damage.

Table 19. Actual Versus Predicted Damage Category

Actual Damage Category	Severe	Moderate	Low	Total
Severe	17	5	0	22
Moderate	0	16	1	17
Low	0	4	18	22
Total	17	25	19	61

6. Discussion

The analysis shows that dunes reduced the likelihood of damage during Hurricane Sandy. Dune width, dune crest height, height of the structure, proximity to structure and type of structure are the strongest predictors. These results were observed from an ordered logistic regression model as well as a multiple linear regression one. The latter violates the assumption of linear regression that the dependent variable be continuous, but nevertheless is a way of examining the consistency of the results.

The research had two major limitations. One was a limited number of cases, and the second is a relatively crude measure of damage. With LIDAR images it is now possible to conduct the same study at many other locations in the United States and even the current admittedly pilot study can be used to help designers identifying types of investments in dunes and other structures.

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APPENDIX A. Data used for dune effectiveness analysis

Zone	Block	Location	Damage Level	Dune (1) or no Dune (0)
1	1	Dover Ave, 2nd Ave	4	1
1	2	2nd Ave, 3rd Ave	4	1
1	3	3rd Ave, 4th Ave	4	1
1	4	4th Ave, 5th Ave	4	1
1	5	5th Ave, 7th Ave	4	1
1	6	7th Ave, 8th Ave	4	1
1	7	8th Ave, 9th Ave	4	1
1	8	9th Ave, Fielder Ave	4	1
1	9	Fielder Ave, Fort Ave	4	1
1	10	Fort Ave, Coolidge Ave	4	1
1	11	Coolidge Ave, Harding Ave	4	1
1	12	Harding Ave, Colony Road	3	1
2	1	Magee Ave, Brown Ave	4	1
2	2	Brown Ave, Camden Ave	3	1
2	3	Camden Ave, Philadelphia Ave	3	1
2	4	Philadelphia Ave, Washington Ave	3	1
2	5	Washington Ave, Brooklyn Ave	4	1
2	6	Brooklyn Ave, New Brunswick Ave	4	1
2	7	New Brunswick Ave, Virginia Ave	4	1
2	8	Virginia Ave, Pennsylvania Ave	4	1
2	9	Pennsylvania Ave, New York Ave	4	1
2	10	New York Ave, New Jersey Ave	4	1
2	11	New Jersey Ave, Jersey City Ave	4	1
2	12	Jersey City Ave, Princeton Ave	4	1
2	13	Princeton Ave, Elizabeth Ave	4	1
2	14	Elizabeth Ave, Newark Ave	4	1
3	1	Plainfield Ave, Bryn Mawr Ave	3	1
3	2	Bryn Mawr Ave, Haddonfield Ave	3	1
3	3	Haddonfield Ave, Westmont Ave	3	1
3	4	Westmont Ave, Ortley Ave	3	1
3	5	Ortley Ave, White Ave	3	1
3	6	White Ave, Kerr Ave	3	1
3	7	Kerr Ave, Bond Ave	3	1
3	8	Bond Ave, Guyer Ave	3	1
3	9	Guyer Ave, President Ave	3	1

3	10	President Ave, Reese Ave	3	1
3	11	Reese Ave, Vance Ave	2	1
3	12	Vance Ave, Magee Ave	3	1
4	1	Ocean Drvie, Cuttyhunk Road	3	1
4	2	Cuttyhunk Road, Bel Air Road	2	1
4	3	Bel Air Road, Osray Lane	2	1
4	4	Osray Lane, Faber Lane	3	1
5	1	J Street, I Street	2	1
5	2	I Street, H Street	2	1
5	3	H Street, G Street	2	1
5	4	G Street, F Street	2	1
5	5	F Street, E Street	2	1
5	6	E Street, D Street	2	1
5	7	D Street, C Street	2	1
5	8	C Street, Brighton Ave	2	1
5	9	Brighton Ave, Island Ave	2	1
5	10	Island Ave, North Ave	2	1
5	11	North Ave, 1st Ave	2	1
5	12	1st Ave, 2nd Ave	2	1
5	13	2nd Ave, 3rd Ave	2	1
5	14	3rd Ave, 4th Ave	2	1
5	15	4th Ave, 5th Ave	2	1
5	16	5th Ave, 6th Ave	2	1
5	17	6th Ave, 7th Ave	2	1
5	18	7th Ave, 8th Ave	2	1
5	19	8th Ave, 9th Ave	2	1
6	1	19th Ave, 18th Ave	3	0
6	2	18th Ave, 17th Ave	4	0
6	3	16th Ave, 15th Ave	2	0
6	4	15th Ave, 14th Ave	2	0
6	5	14st Ave, 13th Ave	2	0
6	6	13th Ave, 12th Ave	4	0
6	7	11th Ave, 10th Ave	4	0
6	8	10th Ave, 9th Ave	3	0
6	9	9th Ave, 8th Ave	4	0
6	10	8th Ave, 7th Ave	4	0
6	11	7th Ave, 6th Ave	4	0
6	12	6th Ave, 5th Ave	4	0
6	13	5th Ave, 4th Ave	4	0

7	1	Pilgrim Pathway, Water St	2	0
7	2	Water St, Brunswick Pl	3	0
7	3	Brunswick Pl, Vetrini Ln	3	0
8	1	Hiering Ave, Sampson Ave	4	0
8	2	Sampson Ave, Carteret Ave	4	0
8	3	Fremont Ave, Hancock Ave	4	0
8	4	Hancock Ave, Sheridan Ave	4	0
8	5	Sheridan Ave, Sherman Ave	4	0
8	6	Sherman Ave, Grant Ave	4	0
8	7	Grant Ave, Blaine Ave	3	0
8	8	Blaine Ave, Sumner Ave	3	0
8	9	Sumner Ave, Webster Ave	3	0
8	10	Webster Ave, Hamilton Ave	3	0
8	11	Hamilton Ave, Franklin Ave	4	0
8	12	Franklin Ave, Lincoln Ave	4	0

APPENDIX B. Ordered Logistic Regression for the relationship between the damage level and existence of a dune system

The LOGISTIC Procedure

Model Information	
Data Set	WORK.DUNE
Response Variable	Damage Level
Number of Response Levels	3
Model	cumulative logit
Optimization Technique	Fisher's scoring

Number of Observations Read	89
Number of Observations Used	89

Response Profile		
Ordered Value	**Damage Level**	**Total Frequency**
1	4	38
2	3	25
3	2	26

Probabilities modeled are cumulated over the lower Ordered Values.

Class Level Information		
Class	**Value**	**Design Variables**
DuneNoDune	**0**	0
	1	1

Model Convergence Status
Convergence criterion (GCONV=1E-8) satisfied.

Score Test for the Proportional Odds Assumption		
Chi-Square	**DF**	**Pr > ChiSq**
0.4273	1	0.5133

Model Fit Statistics		
Criterion	**Intercept Only**	**Intercept and Covariates**
AIC	196.156	193.166
SC	201.133	200.632
-2 Log L	192.156	187.166

R-Square	0.0545	**Max-rescaled R-Square**	0.0616

Testing Global Null Hypothesis: BETA=0			
Test	**Chi-Square**	**DF**	**Pr > ChiSq**
Likelihood Ratio	4.9898	1	0.0255
Score	4.9396	1	0.0262
Wald	4.7093	1	0.0300

Type 3 Analysis of Effects			
Effect	**DF**	**Wald Chi-Square**	**Pr > ChiSq**
DuneNoDune	1	4.7093	0.0300

Analysis of Maximum Likelihood Estimates						
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept	**4**	1	0.3454	0.3740	0.8525	0.3558
Intercept	**3**	1	1.5787	0.4085	14.9345	0.0001
DuneNoDune	**1**	1	-0.9620	0.4433	4.7093	0.0300

Odds Ratio Estimates			
Effect	**Point Estimate**	**95% Wald Confidence Limits**	
DuneNoDune 1 vs 0	0.382	0.160	0.911

Association of Predicted Probabilities and Observed Responses			
Percent Concordant	30.9	**Somers' D**	0.181
Percent Discordant	12.8	**Gamma**	0.413
Percent Tied	56.3	**Tau-a**	0.120
Pairs	2588	**c**	0.590

APPENDIX C. Data used for dune characteristic analysis

Zone	Block	Damage Level	Beach Width	Dune Width	Dune Crest Height	Height of Infrastructure	Presence of Structure	Foredune Scrap Slope	Gaps Between Dunes	Proximity to Structure
1	1	4	172.50	74.00	17.00	41.00	1	9.10	35.00	55.00
1	2	4	115.50	61.10	18.50	15.00	0	13.40	24.00	194.20
1	3	4	104.50	43.20	18.50	15.00	0	11.80	26.00	176.80
1	4	4	81.50	47.50	16.50	15.00	0	16.90	25.00	93.60
1	5	4	142.50	46.10	14.00	41.50	1	11.90	280.30	90.00
1	6	4	101.50	49.80	17.50	16.00	0	12.40	22.00	79.90
1	7	4	100.50	70.00	18.00	16.00	0	18.70	23.50	82.00
1	8	4	68.00	50.30	18.00	42.00	1	16.80	30.30	60.40
1	9	4	85.50	37.30	16.50	14.50	0	12.10	27.70	71.60
1	10	4	118.50	58.90	20.00	13.00	0	9.60	18.90	81.50
1	11	4	145.00	64.60	18.50	39.00	1	13.30	34.10	53.30
1	12	3	127.50	169.20	27.00	39.00	1	15.20	0.00	74.00
2	1	4	167.00	51.20	24.00	13.50	0	9.00	23.90	69.30
2	2	3	142.00	49.50	20.50	13.00	0	10.60	32.30	37.80
2	3	3	120.50	46.00	24.00	13.50	0	14.80	63.60	47.00
2	4	3	128.00	49.40	20.50	13.50	0	14.40	29.20	37.10
2	5	4	124.00	55.60	21.50	13.50	0	15.40	26.30	52.70
2	6	4	139.00	51.40	20.50	13.50	0	13.40	25.40	43.70
2	7	4	139.00	39.00	19.50	13.50	0	13.40	26.20	44.70
2	8	4	135.50	38.90	20.00	13.50	0	12.80	22.40	38.90
2	9	4	136.00	28.60	19.00	13.50	0	11.70	17.00	48.60
2	10	4	141.00	28.00	18.00	13.50	0	11.80	18.40	42.30
2	11	4	111.50	30.10	18.50	13.50	0	15.10	8.10	44.60

2	12	4	126.50	34.30	16.50	13.50	0	13.10	19.00	171.10
2	13	4	167.00	33.40	16.50	13.50	0	8.90	28.80	60.00
2	14	4	139.50	24.80	17.50	13.00	0	14.90	23.80	41.00
3	1	3	149.00	143.10	28.50	41.00	1	8.30	42.70	0.00
3	2	3	148.50	138.70	26.50	41.00	1	12.00	39.60	0.00
3	3	3	160.00	143.90	27.00	41.00	1	11.30	44.90	0.00
3	4	3	157.00	113.40	28.00	41.00	1	12.30	38.90	0.00
3	5	3	137.00	87.40	24.50	16.50	0	11.60	23.40	42.90
3	6	3	119.50	72.60	25.00	17.00	0	16.20	22.30	63.90
3	7	3	109.50	89.10	24.00	14.50	0	16.80	16.90	52.40
3	8	3	139.50	90.30	22.50	14.00	0	11.90	37.30	51.60
3	9	3	148.00	52.80	23.50	14.00	0	13.10	29.10	43.40
3	10	3	129.50	73.30	23.00	14.00	0	15.30	24.30	82.80
3	11	2	111.50	52.50	22.00	14.00	0	15.00	45.70	51.00
3	12	3	110.50	52.90	21.50	13.50	0	15.80	34.60	53.70
4	1	3	136.50	161.00	22.50	36.00	1	10.40	57.60	0.00
4	2	2	117.00	133.90	23.00	36.00	1	12.30	0.00	0.00
4	3	2	117.00	124.60	26.50	36.00	1	16.90	0.00	0.00
4	4	3	126.00	94.90	21.00	36.00	1	13.50	0.00	0.00
5	1	2	146.50	83.00	22.00	15.00	0	11.00	15.00	136.30
5	2	2	130.50	90.40	23.00	14.50	0	13.10	36.00	129.90
5	3	2	166.50	87.80	23.50	14.50	0	11.10	0.00	135.80
5	4	2	158.00	85.80	22.50	14.50	0	10.00	55.25	122.30
5	5	2	161.50	96.20	25.00	14.50	0	13.00	0.00	121.30
5	6	2	155.50	105.50	24.50	16.50	0	10.90	27.80	149.20
5	7	2	195.00	107.60	25.50	16.50	0	10.10	0.00	140.30
5	8	2	148.00	106.80	24.00	16.50	0	11.20	46.60	118.80
5	9	2	143.50	113.90	24.50	16.50	0	12.10	0.00	108.00
5	10	2	154.00	115.60	25.00	16.50	0	11.70	39.90	180.30
5	11	2	180.00	134.60	26.00	16.50	0	9.90	0.00	182.00

5	12	2	153.00	124.90	25.50	16.00	0	11.00	29.70	173.30
5	13	2	179.50	122.50	25.00	16.00	0	10.10	0.00	144.80
5	14	2	144.50	128.80	26.00	16.00	0	11.60	0.00	144.90
5	15	2	138.00	118.90	25.00	16.00	0	12.60	31.20	114.90
5	16	2	173.50	106.90	26.00	16.00	0	11.30	0.00	117.30
5	17	2	171.00	96.70	25.50	15.50	0	12.00	36.10	114.60
5	18	2	173.00	97.40	25.00	14.00	0	12.40	0.00	103.20

APPENDIX D. Multiple linear regression for Model 1

The REG Procedure
Dependent Variable: DamageLevel

Number of Observations Read	61
Number of Observations Used	61

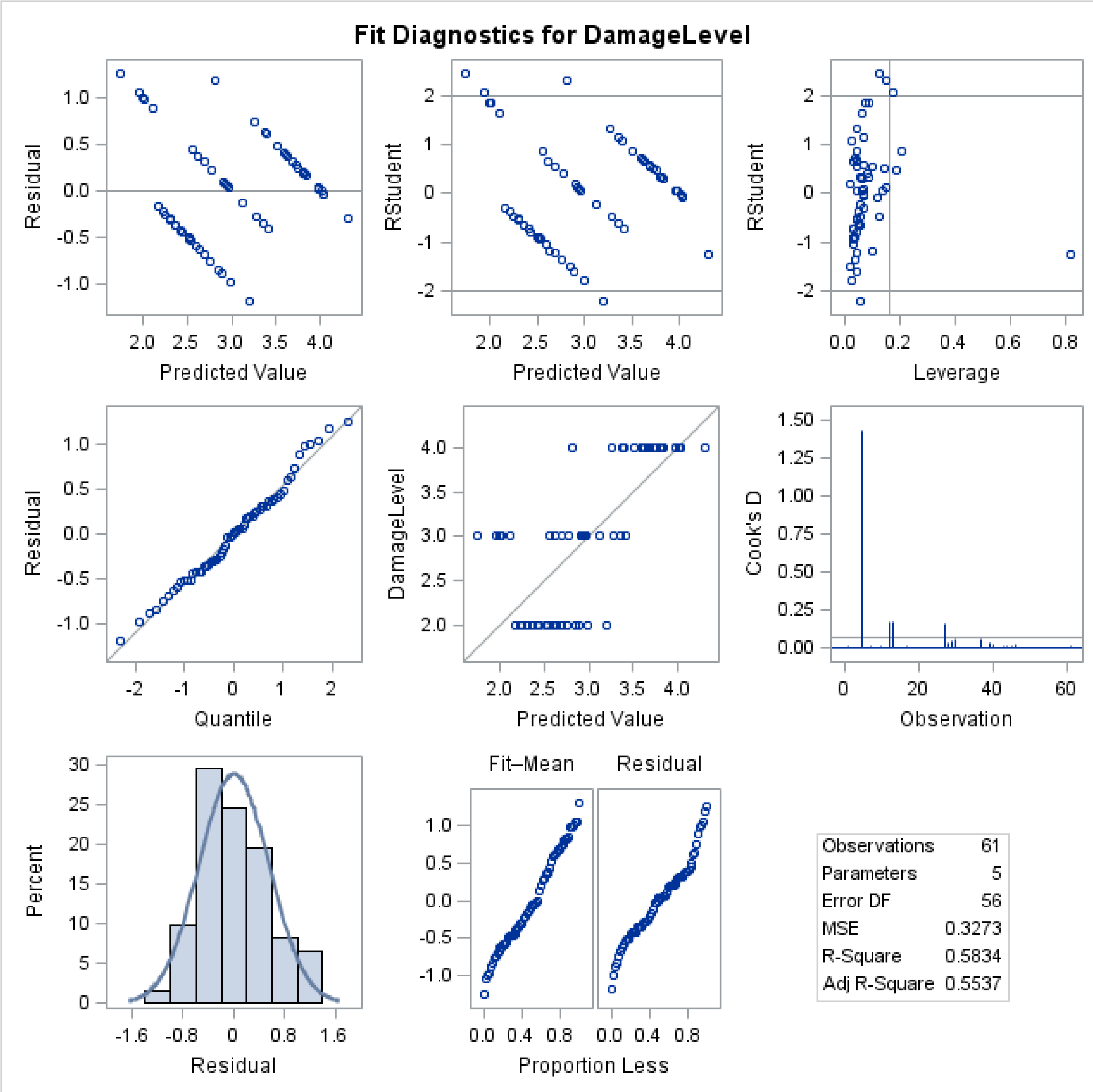
Analysis of Variance

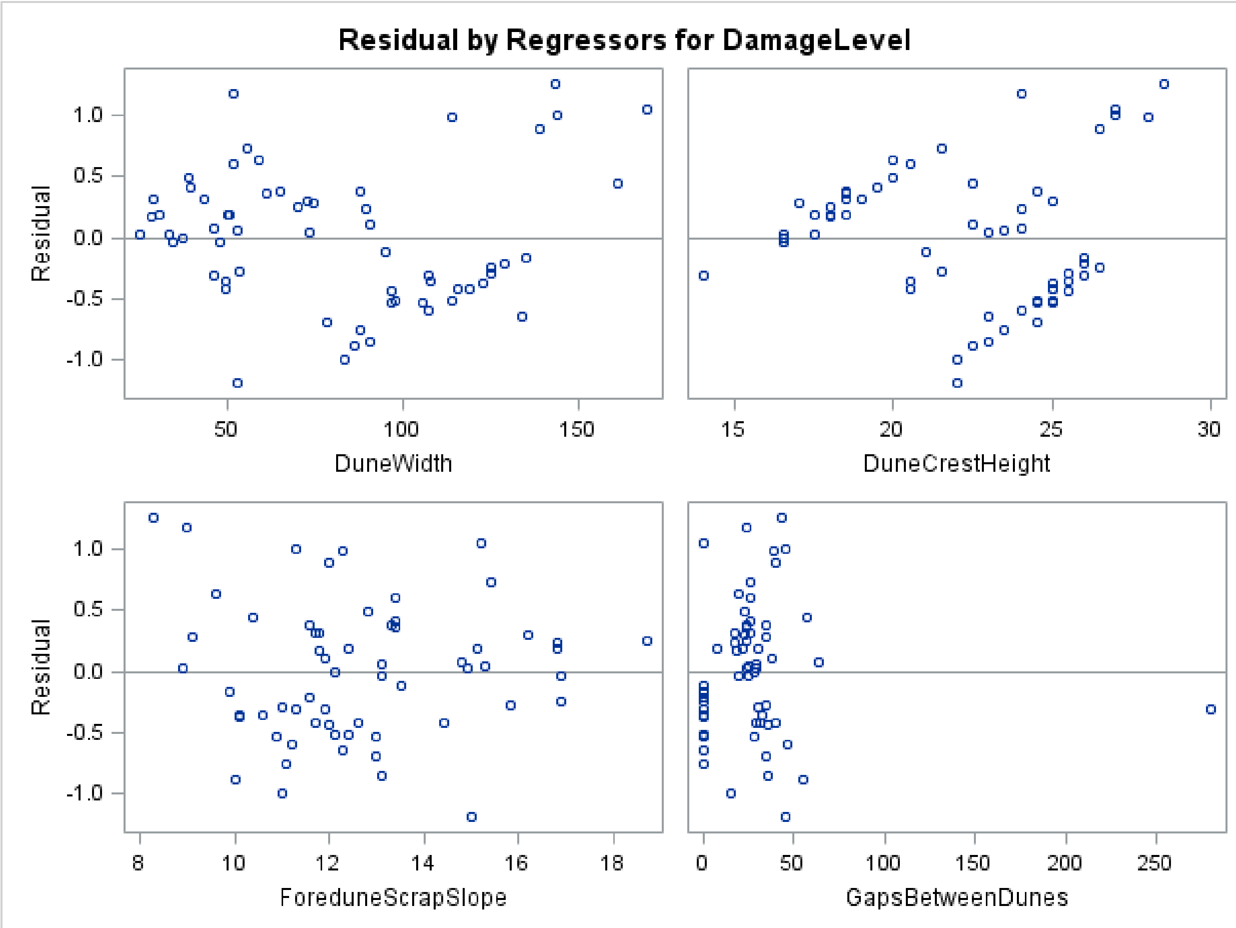
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	25.67162	6.41790	19.61	<.0001
Error	56	18.32838	0.32729		
Lack of Fit	56	18.32838	0.32729	.	.
Pure Error	0	0	.		
Corrected Total	60	44.00000			

Root MSE	0.57209	**R-Square**	0.5834
Dependent Mean	3.00000	**Adj R-Sq**	0.5537
Coeff Var	19.06983		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	**1**	6.35735	0.79872	7.96	<.0001
DuneWidth	**1**	-0.00457	0.00330	-1.38	0.1719
DuneCrestHeight	**1**	-0.14377	0.03605	-3.99	0.0002
ForeduneScrapSlope	**1**	0.01630	0.03385	0.48	0.6321
GapsBetweenDunes	**1**	-0.00007320	0.00216	-0.03	0.9730


Fit Diagnostics for DamageLevel
Residual
Predicted Value
RStudent
Predicted Value
RStudent
Leverage
Residual
Quantile
DamageLevel
Predicted Value
Cook's D
Observation
Percent
Residual
Fit–Mean
Residual
Proportion Less
Observations 61
Parameters 5
Error DF 56
MSE 0.3273
R-Square 0.5834
Adj R-Square 0.5537


Residual by Regressors for DamageLevel
Residual
1.0
0.5
0.0
-0.5
-1.0
50
100
150
DuneWidth
15
20
25
30
DuneCrestHeight
8
10
12
14
16
18
ForeduneScrapSlope
0
50
100
150
200
250
GapsBetweenDunes

APPENDIX E. Ordered Logistic Regression for Model 1

The LOGISTIC Procedure

Model Information	
Data Set	WORK.SANDY4
Response Variable	DamageLevel
Number of Response Levels	3
Model	cumulative logit
Optimization Technique	Fisher's scoring

Number of Observations Read	61
Number of Observations Used	61

Response Profile

Ordered Value	DamageLevel	Total Frequency
1	4	22
2	3	17
3	2	22

Probabilities modeled are cumulated over the lower Ordered Values.

Model Convergence Status
Convergence criterion (GCONV=1E-8) satisfied.

Score Test for the Proportional Odds Assumption

Chi-Square	DF	Pr > ChiSq
15.0730	4	0.0046

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	137.186	97.212
SC	141.407	109.877

Model Fit Statistics		
Criterion	**Intercept Only**	**Intercept and Covariates**
-2 Log L	133.186	85.212

R-Square	0.5445	**Max-rescaled R-Square**	0.6137

Testing Global Null Hypothesis: BETA=0			
Test	**Chi-Square**	**DF**	**Pr > ChiSq**
Likelihood Ratio	47.9736	4	<.0001
Score	35.5902	4	<.0001
Wald	27.7168	4	<.0001

Analysis of Maximum Likelihood Estimates						
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept	**4**	1	10.2401	3.4537	8.7909	0.0030
Intercept	**3**	1	12.6011	3.6261	12.0765	0.0005
DuneWidth		1	-0.00871	0.0128	0.4659	0.4949
DuneCrestHeight		1	-0.5538	0.1616	11.7362	0.0006
ForeduneScrapSlope		1	0.0931	0.1440	0.4177	0.5181
GapsBetweenDunes		1	0.0217	0.0180	1.4511	0.2284

Odds Ratio Estimates			
Effect	**Point Estimate**	**95% Wald Confidence Limits**	
DuneWidth	0.991	0.967	1.016
DuneCrestHeight	0.575	0.419	0.789
ForeduneScrapSlope	1.098	0.828	1.456
GapsBetweenDunes	1.022	0.987	1.059

Association of Predicted Probabilities and Observed Responses			
Percent Concordant	87.3	**Somers' D**	0.748
Percent Discordant	12.6	**Gamma**	0.748
Percent Tied	0.1	**Tau-a**	0.503
Pairs	1232	**c**	0.874

APPENDIX F. Multiple linear regression for Model 2

The REG Procedure
Dependent Variable: DamageLevel

Number of Observations Read	61
Number of Observations Used	61

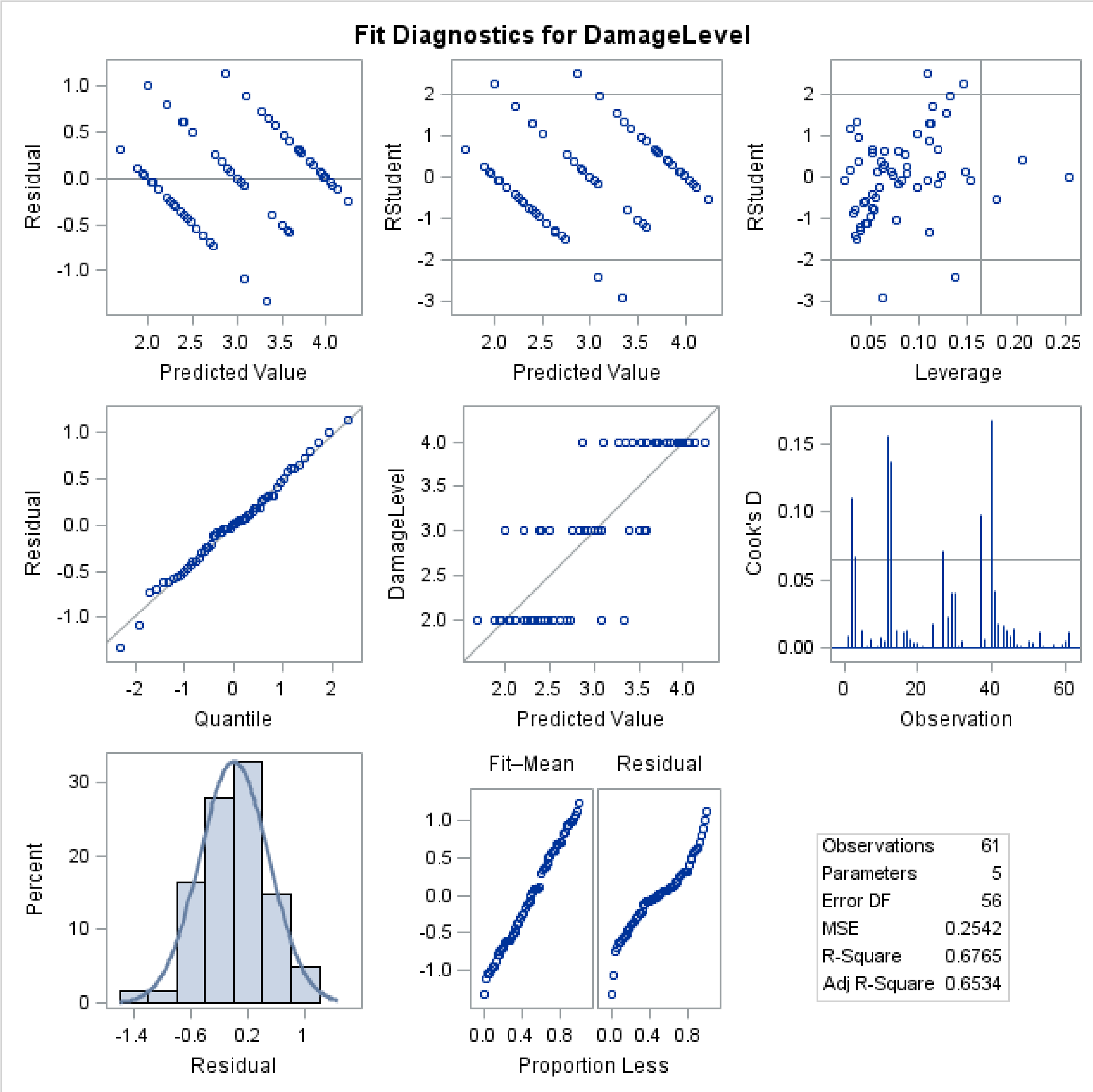
Analysis of Variance

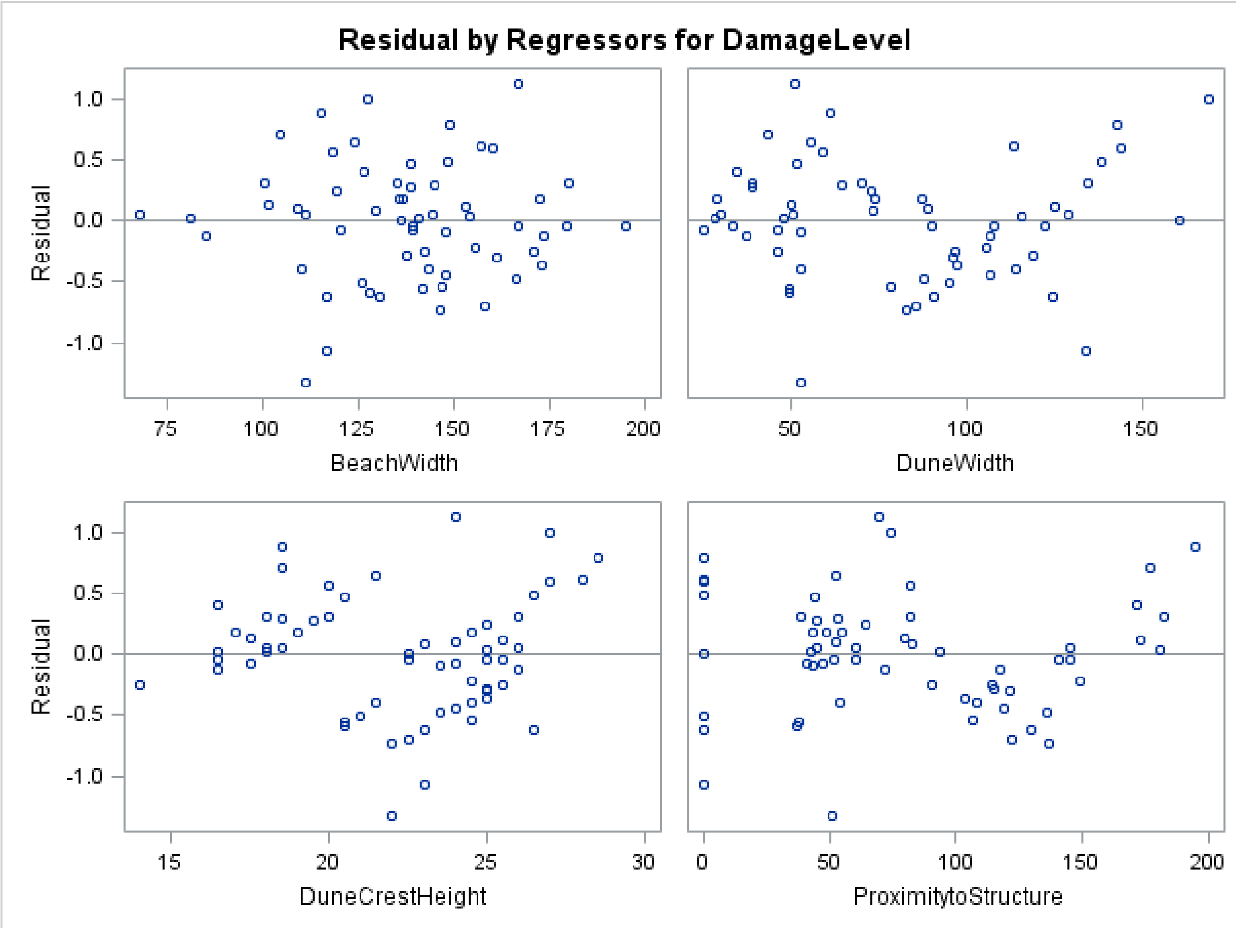
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	29.76637	7.44159	29.28	<.0001
Error	56	14.23363	0.25417		
Lack of Fit	56	14.23363	0.25417	.	.
Pure Error	0	0	.		
Corrected Total	60	44.00000			

Root MSE	0.50415	**R-Square**	0.6765
Dependent Mean	3.00000	**Adj R-Sq**	0.6534
Coeff Var	16.80516		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	**1**	7.09154	0.55247	12.84	<.0001
BeachWidth	**1**	-0.00182	0.00302	-0.60	0.5487
DuneWidth	**1**	-0.00420	0.00284	-1.48	0.1451
DuneCrestHeight	**1**	-0.14072	0.03198	-4.40	<.0001
ProximitytoStructure	**1**	-0.00470	0.00126	-3.73	0.0004


Fit Diagnostics for DamageLevel
Residual
Predicted Value
RStudent
Leverage
Quantile
DamageLevel
Cook's D
Observation
Percent
Residual
Fit–Mean
Proportion Less
Observations 61
Parameters 5
Error DF 56
MSE 0.2542
R-Square 0.6765
Adj R-Square 0.6534


Residual by Regressors for DamageLevel
Residual
BeachWidth
DuneWidth
DuneCrestHeight
ProximitytoStructure
1.0
0.5
0.0
-0.5
-1.0
75
100
125
150
175
200
50
100
150
15
20
25
30
0
50
100
150
200

APPENDIX G. Ordered Logistic Regression for Model 2

The LOGISTIC Procedure

Model Information	
Data Set	WORK.SANDY5
Response Variable	DamageLevel
Number of Response Levels	3
Model	cumulative logit
Optimization Technique	Fisher's scoring

Number of Observations Read	61
Number of Observations Used	61

Response Profile

Ordered Value	DamageLevel	Total Frequency
1	4	22
2	3	17
3	2	22

Probabilities modeled are cumulated over the lower Ordered Values.

Model Convergence Status
Convergence criterion (GCONV=1E-8) satisfied.

Score Test for the Proportional Odds Assumption

Chi-Square	DF	Pr > ChiSq
22.0521	4	0.0002

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	137.186	84.489
SC	141.407	97.154

Model Fit Statistics		
Criterion	**Intercept Only**	**Intercept and Covariates**
-2 Log L	133.186	72.489

R-Square	0.6303	**Max-rescaled R-Square**	0.7103

Testing Global Null Hypothesis: BETA=0			
Test	**Chi-Square**	**DF**	**Pr > ChiSq**
Likelihood Ratio	60.6968	4	<.0001
Score	41.2670	4	<.0001
Wald	29.4388	4	<.0001

Analysis of Maximum Likelihood Estimates						
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept	**4**	1	15.6275	3.4983	19.9559	<.0001
Intercept	**3**	1	18.5089	3.8795	22.7617	<.0001
BeachWidth		1	-0.00970	0.0169	0.3282	0.5667
DuneWidth		1	-0.0151	0.0129	1.3707	0.2417
DuneCrestHeight		1	-0.5735	0.1743	10.8281	0.0010
ProximitytoStructure		1	-0.0218	0.00672	10.5603	0.0012

Odds Ratio Estimates			
Effect	**Point Estimate**	**95% Wald Confidence Limits**	
BeachWidth	0.990	0.958	1.024
DuneWidth	0.985	0.960	1.010
DuneCrestHeight	0.564	0.401	0.793
ProximitytoStructure	0.978	0.966	0.991

Association of Predicted Probabilities and Observed Responses			
Percent Concordant	91.6	**Somers' D**	0.831
Percent Discordant	8.4	**Gamma**	0.831
Percent Tied	0.0	**Tau-a**	0.560
Pairs	1232	**c**	0.916

APPENDIX H. Multiple linear regression for dune characteristic analysis

The REG Procedure
Dependent Variable: DamageLevel

Number of Observations Read	61
Number of Observations Used	61

Analysis of Variance

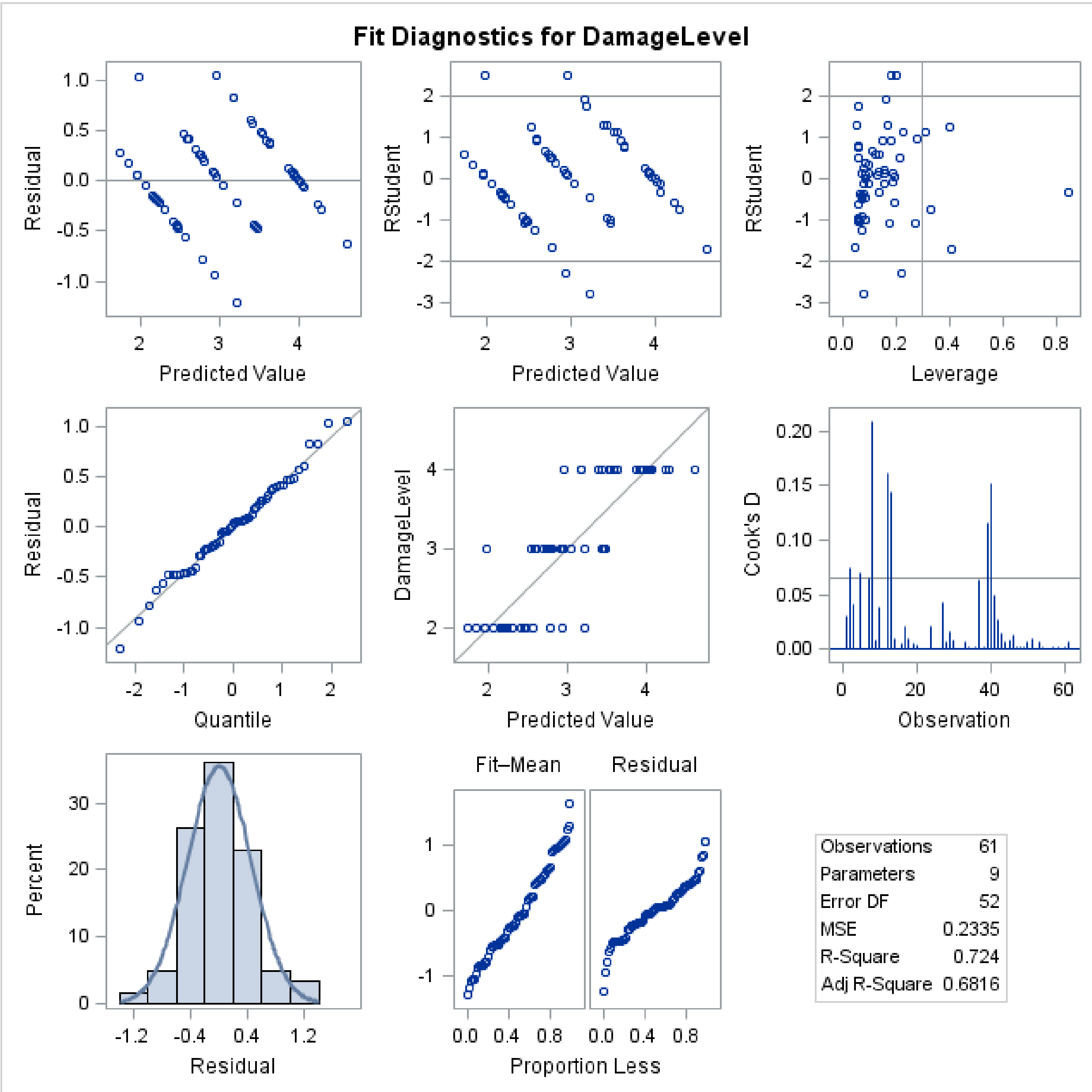
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	31.85672	3.98209	17.05	<.0001
Error	52	12.14328	0.23352		
Lack of Fit	52	12.14328	0.23352		
Pure Error	0	0			
Corrected Total	60	44.00000			

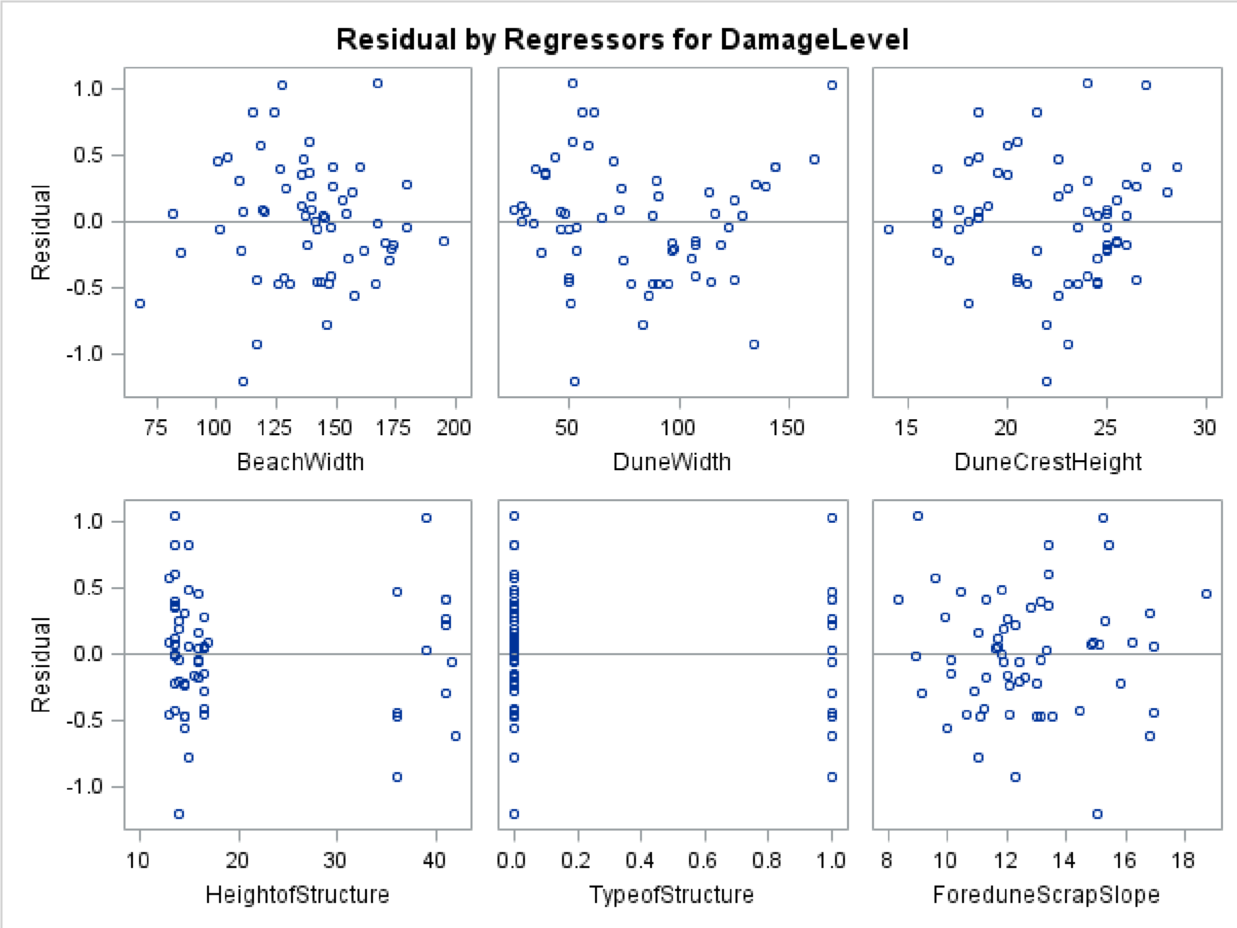
Root MSE	0.48324	**R-Square**	0.7240
Dependent Mean	3.00000	**Adj R-Sq**	0.6816
Coeff Var	16.10813		

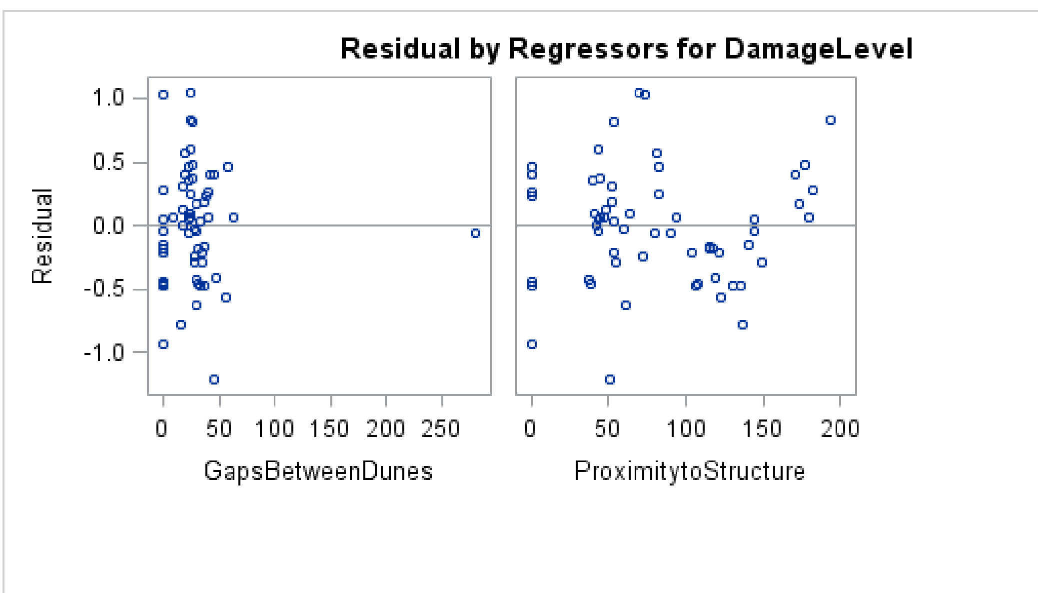
Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	**1**	6.26905	1.08224	5.79	<.0001
BeachWidth	**1**	-0.00399	0.00400	-1.00	0.3235
DuneWidth	**1**	-0.01001	0.00405	-2.47	0.0168
DuneCrestHeight	**1**	-0.11527	0.03978	-2.90	0.0055
HeightofStructure	**1**	0.09861	0.05030	1.96	0.0553
TypeofStructure	**1**	-1.95109	1.30867	-1.49	0.1420
ForeduneScrapSlope	**1**	-0.03870	0.03987	-0.97	0.3362
GapsBetweenDunes	**1**	-0.00314	0.00203	-1.54	0.1289
ProximitytoStructure	**1**	-0.00401	0.00188	-2.13	0.0375

Sum of Residuals	0
Sum of Squared Residuals	12.14328
Predicted Residual SS (PRESS)	17.63292




Residual by Regressors for DamageLevel
Residual
BeachWidth
DuneWidth
DuneCrestHeight
HeightofStructure
TypeofStructure
ForeduneScrapSlope


Residual by Regressors for DamageLevel
Residual
GapsBetweenDunes
ProximitytoStructure

APPENDIX I. Ordered logistic regression for dune characteristic analysis

The LOGISTIC Procedure

Model Information	
Data Set	WORK.SANDY5
Response Variable	DamageLevel
Number of Response Levels	3
Model	cumulative logit
Optimization Technique	Fisher's scoring

Number of Observations Read	61
Number of Observations Used	61

Response Profile

Ordered Value	DamageLevel	Total Frequency
1	4	22
2	3	17
3	2	22

Probabilities modeled are cumulated over the lower Ordered Values.

Class Level Information

Class	Value	Design Variables
TypeofStructure	**0**	0
	1	1

Model Convergence Status
Convergence criterion (GCONV=1E-8) satisfied.

Score Test for the Proportional Odds Assumption

Chi-Square	DF	Pr > ChiSq
14.0232	8	0.0812

Model Fit Statistics		
Criterion	**Intercept Only**	**Intercept and Covariates**
AIC	137.186	81.172
SC	141.407	102.280
-2 Log L	133.186	61.172

R-Square	0.6929	**Max-rescaled R-Square**	0.7809

Testing Global Null Hypothesis: BETA=0			
Test	**Chi-Square**	**DF**	**Pr > ChiSq**
Likelihood Ratio	72.0141	8	<.0001
Score	42.7656	8	<.0001
Wald	24.9229	8	0.0016

Type 3 Analysis of Effects			
Effect	**DF**	**Wald Chi-Square**	**Pr > ChiSq**
BeachWidth	1	2.2128	0.1369
DuneWidth	1	5.2722	0.0217
DuneCrestHeight	1	5.1052	0.0239
HeightofStructure	1	6.0895	0.0136
TypeofStructure	1	4.0463	0.0443
ForeduneScrapSlope	1	0.1945	0.6592
GapsBetweenDunes	1	0.0134	0.9077
ProximitytoStructure	1	2.4104	0.1205

Analysis of Maximum Likelihood Estimates						
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept	**4**	1	11.7409	6.3417	3.4276	0.0641
Intercept	**3**	1	15.0483	6.5413	5.2924	0.0214

Analysis of Maximum Likelihood Estimates						
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald Chi-Square**	**Pr > ChiSq**
BeachWidth		1	-0.0470	0.0316	2.2128	0.1369
DuneWidth		1	-0.0528	0.0230	5.2722	0.0217
DuneCrestHeight		1	-0.5566	0.2463	5.1052	0.0239
HeightofStructure		1	0.7960	0.3226	6.0895	0.0136
TypeofStructure	**1**	1	-15.6847	7.7974	4.0463	0.0443
ForeduneScrapSlope		1	-0.1028	0.2330	0.1945	0.6592
GapsBetweenDunes		1	0.00268	0.0232	0.0134	0.9077
ProximitytoStructure		1	-0.0166	0.0107	2.4104	0.1205

Odds Ratio Estimates			
Effect	**Point Estimate**	**95% Wald Confidence Limits**	
BeachWidth	0.954	0.897	1.015
DuneWidth	0.949	0.907	0.992
DuneCrestHeight	0.573	0.354	0.929
HeightofStructure	2.217	1.178	4.172
TypeofStructure 1 vs 0	<0.001	<0.001	0.669
ForeduneScrapSlope	0.902	0.572	1.425
GapsBetweenDunes	1.003	0.958	1.049
ProximitytoStructure	0.984	0.963	1.004

Association of Predicted Probabilities and Observed Responses			
Percent Concordant	94.1	**Somers' D**	0.882
Percent Discordant	5.8	**Gamma**	0.883
Percent Tied	0.1	**Tau-a**	0.594
Pairs	1232	**c**	0.941